CFD Analysis of Stirling Type Inertance Tube Pulse Tube Refrigerator

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A Thesis submitted in partial fulfillment of
the requirements for the award of the degree of

Master of Technology in
Cryogenics and Vacuum Technology

Submitted to

National Institute of Technology Rourkela

By

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Prof. R.K.Sahoo

May 2016

Certificate

This is to certify that the work in the thesis entitled '*CFD Analysis of Stirling Type Inertance Tube Pulse Refrigerator*' by *Abinash Khandual*, bearing Roll Number *214ME5353*, is a record of an original research work carried out by him under my supervision and guidance in partial fulfilment of the requirements for the award of the degree of *Master of Technology* in *Cryogenics and Vacuum Technology, Department of Mechanical Engineering*. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

R.K. Sahoo

Acknowledgement

Firstly, I would like to convey my heartily thanks and gratitude to my beloved guide, Prof. R.K. Sahoo, (Dept. of Mechanical Engineering, NIT, Rourkela) for his continuous guidance and support, with the help of which I have successfully been able to complete my research work.

I would like to acknowledge my special thanks to the Head of the Department, Prof. S.S. Mahapatra and all the faculty members of the Department of Mechanical Engineering, for providing me the deep insight and discernments given through the various courses they taught and also for their valuable guidance during my work.

I am also thankful to the Ph.D. scholar Mr. Pankaj Kumar whose timely help and cooperation allowed me to complete my research work in time and bring out this thesis. My special thanks to the staff of Mechanical Engineering Department.

In the end, I would like to profound my deepest gratitude to my family for their exceptional love and encouragement throughout this entire journey, without which I would have struggled to find the inspiration and motivation needed to complete this thesis.

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Cryogenics and Vacuum Technology

Abstract

Pulse tube cryocooler are generally one dimensional flow fields. By using two stage pulse tube cryocooler one can reach up to very low temperature. In it the compression and expansion of gas inside the pulse tube generates the required temperature. The main advantage of using pulse tube is that it does not have any moving parts inside the pulse tube rather oscillations of gas inside it does the job. All pulse tube cryocooler are of closed cycle type so no mass gets exit during the complete cycle. There is only one moving component named as piston which goes to and fro motion to generate the required pressure variation. Generally helium is used as the working fluid to reach a very low temperature of around 4.2k. The calculations for design are done based on one dimensional flow model. In the Stirling type pulse tube cryocooler an inertance tube, two number of opposed piston compressor, Regenerator, pulse tube, cold end heat exchanger and hot end heat exchanger mainly. The simulation work is done of a fully coupled system operating in steady mode. In this ANSYS Fluent is used to study the flow analysis and heat transfer phenomena inside the pulse tube cryocooler. A 2D axis symmetry geometry of the pulse tube is considered for the CFD simulation. The external boundary condition used is a sinusoidal oscillating piston velocity by developing an UDF, which is accompanied by thermal and adiabatic condition with a known heat flux at the cold end heat exchanger. The aim is to check the performance of ITPTR based on CFD simulations.

Keywords: Pulse tube; Cryocooler ; CFD; ITPTR

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Nomenclature:

Symbols	***Quantity***	***SI unit***
$\bar{\bar{C}}$	*inertial drag coefficient tensors*	m^{-1}
h	*enthalpy*	*J/kg*
j	*superficial velocity*	*m/s*
k	*thermal conductivity*	*W/mK*
p	*Pressure*	N/m^2
T	*Temperature*	*K*
t	*Time*	*s*
v	*intrinsic velocity*	*m/s*
ω	*angular frequency*	*rad/s*
x	*piston displacement*	*m*
x_a	*piston displacement amplitude*	*m*
$\bar{\bar{\beta}}$	*permeability tensors*	M^2
ε	*porosity*	-
μ	*absolute viscosity*	*kg/ms*
ρ	*density*	kg/m^3
$\bar{\bar{\tau}}$	*Stress tensors*	N/m^2
f	*fluid*	-

Chapter 1

Introduction

1.1 General:

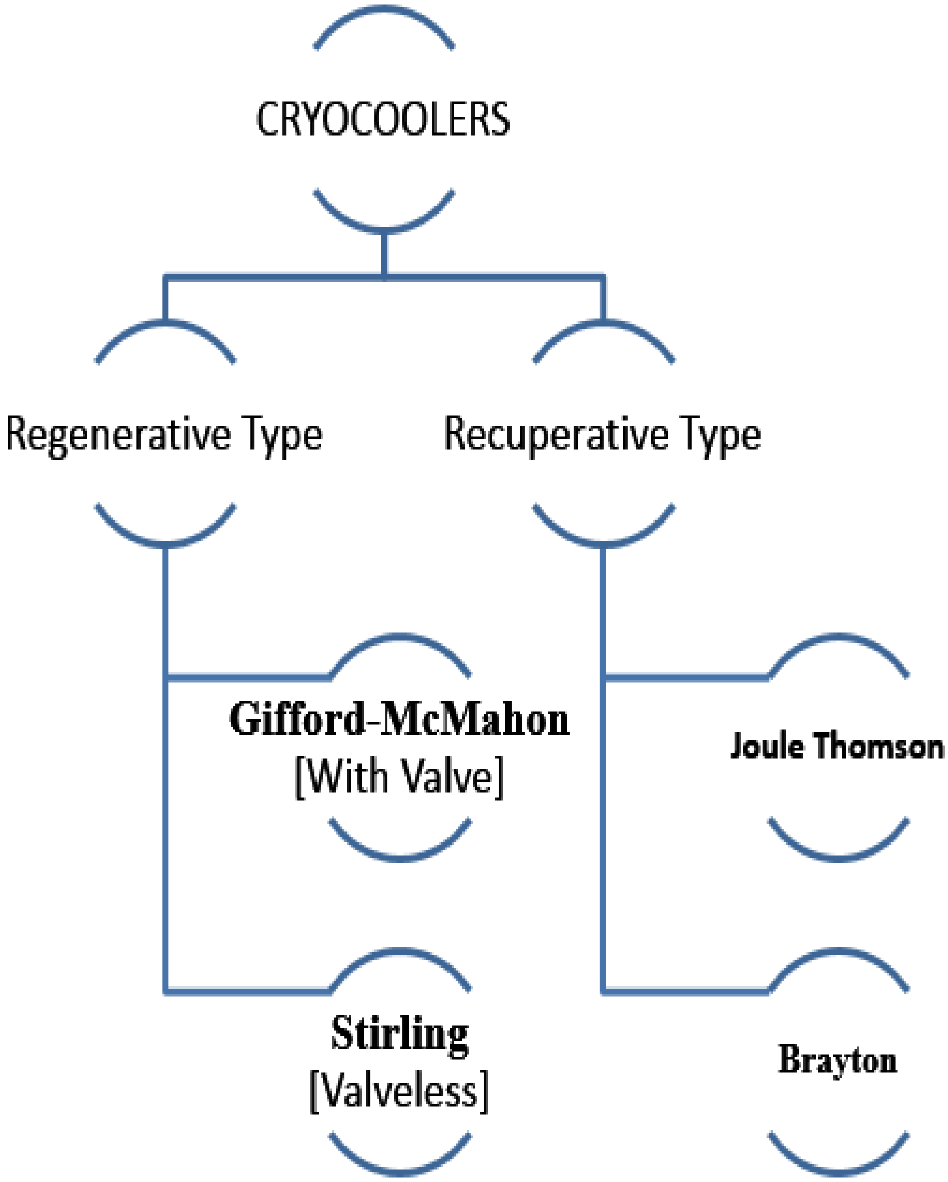
Cryogenics is the generation of very low temperature below 123K. This temperature is defined broadly because beyond 123K the gas can be liquefied by applying high pressure but below 123K the cryogenic fluids cannot be liquefied by applying high pressure. It came from the Greek word 'kryos' which means 'frost' and 'genics' means 'to produce.' It implicates refrigeration, liquefaction, storage and transport of cryogenic fluids, cryostat design and the study of phenomena that occur at these temperatures.

123K

CRYOGENICS	REFRIGERATION
Oxygen (90 K)	R134a (246 K)
Air (78 K)	R12 (243 K)
Nitrogen (77 K)	R22 (233K)
Hydrogen (20 K)	Propane (231K)
Helium (4.2 K)	Ethane (184K)

[Liquefaction Temperature of various gases.]

Cryocooler is a mechanical device in which low temperature is produced by compression and expansion of gas. It is a closed operated cycle, which means the mass of the working gas is constant. It has mainly three components an expander, an heat exchanger and a compressor. The cold generated in the expander is exchanged between the cold end and the object to be cooled using an evaporator. Usually the low temperature generated at the cold end is exchanged between the evaporator and the object to be cooled. Usually the cryocooler is classified broadly in to two type's one regenerative type and other recuperative type. Usually cryocooler will replace cryogens below 77K or below 4.2K temperature. Cryocooler is used generally where no cryogen is required. They operate at reliable and with maintenance free condition. The demand of cryoccoler are increasing because the cost of cryogen is going up. In Regenerative type cryocooler GM pulse tube type and Stirling pulse tube type cooler is there. GM type cryocooler are usually with valves and Stirling type pulse tube are generally valve less type. In Recuperative type J-T type and Claude systems are divided. These cryocooler are specifically used in the cooling of superconductor and semiconductors, as well as cooling of the infrared sensors in the missile guided system & satellite-based supervision, SQUID (superconducting quantum interference device), cry pumps, superconducting magnets, cooling of radiation shields, etc...



i.Military

- Super conducting magnets for mine sweeping
- Infrared sensors for missile guidance & night vision
- Gamma-ray sensors for monitoring nuclear activity

ii.Healthcare

- Cooling superconducting magnets for MRI
- Cryogenic catheters and cryosurgery
- SQUID magnetometers for heart and brain studies
- Liqudfaction of oxygen for hospital and home use

iii.Energy

- Infrared sensors for thermal loss measurements
- Superconducting power applications
- LNG for peak shaving

iv.Commercial

- Superconductors for cellular-phone base stations and voltage standards
- Superconductors for high-speed communications
- Infrared sensors for NDE and process monitoring
- Semiconductors for high-speed computers
- Cryopumps for semiconductor fabrication

v.Environment

- Infrared sensors for pollution monitoring
- Infrared sensors for satellites

vi.Transportation

- Superconducting magnets in maglev trains
- Infrared sensors for aircraft night vision
- Liqudfied Nitrogen Gas for fleet vehicles

The main concern is to increase the efficiency of the cryocooler for better performance. GM type and Stirling type have been used in numerous applications. But these cryocooler have moving parts at the cold end which somehow decreases the efficiency, so if we remove the moving part at the cold end thereby increasing the efficiency. So here Pulse tube type are used where at the cold end there is no moving part hence increasing the efficiency. Here the gas by repeated compression and expansion inside the pulse tube generates the required low temperature.

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1.2 Stirling and G- M type Cryocoolers:

Stirling type Cryocooler

- i.Works at high frequency (20-150 Hz)
- ii.Compressor directly connected to expander
- iii.Pressure ratios are low
- iv.Miniaturization is possible due to fewer moving parts.
- v.Low power compressors and compact.
- vii.Use of Dry compressor
- vii.Suitable for space application

G-M type cryocooler

- i.Works at low frequency (2-5 Hz)
- ii.Compressor connected to expander through a valve
- iii.Miniaturization is not possible due to the valves.
- iv.Pressure ratios are High
- v.High power compressors and bulky
- vi.Use of Lubricated compressor
- vii.Mostly used in land based application

1.3 Pulse Tube Cryocooler:

Scientist Gifford and Longsworth first noticed some effect of cooling at one end and pulsating pressure at the other end of a hollow tube in the year 1963. This lead to the initiation of the first type of cryogenic refrigerators known as 'Basic pulse tube refrigerator (BPTR).' The pulse tube system became one of the most significant subjects in the field of cryogenics refrigeration primarily due to following two reasons, i.e. it has no moving parts in the cold temperature region and the advantages of simplicity and enhanced reliability. The primary skills of this new device, as in comparison with conventional Stirling and Gifford-McMahon systems, is its reliability and long life as a result of the absence of moving part at low-temperature region.

- ➢ Working Principle of the Pulse Tube Refrigerators-

  Pulse tube refrigerator are analysed by first order phasor analysis then second order Isothermal model, Thermodynamic non symmetry effect and third order analysis is numerical method and CFD analysis. There is a phase shift mechanism involved in pulse tube cryocooler. So in Pulse tube cryocooler there is Stirling type pulse tube cryocooler and GM type pulse tube cryocooler. Stirling type are generally high frequency machines where as GM type are low frequency types.

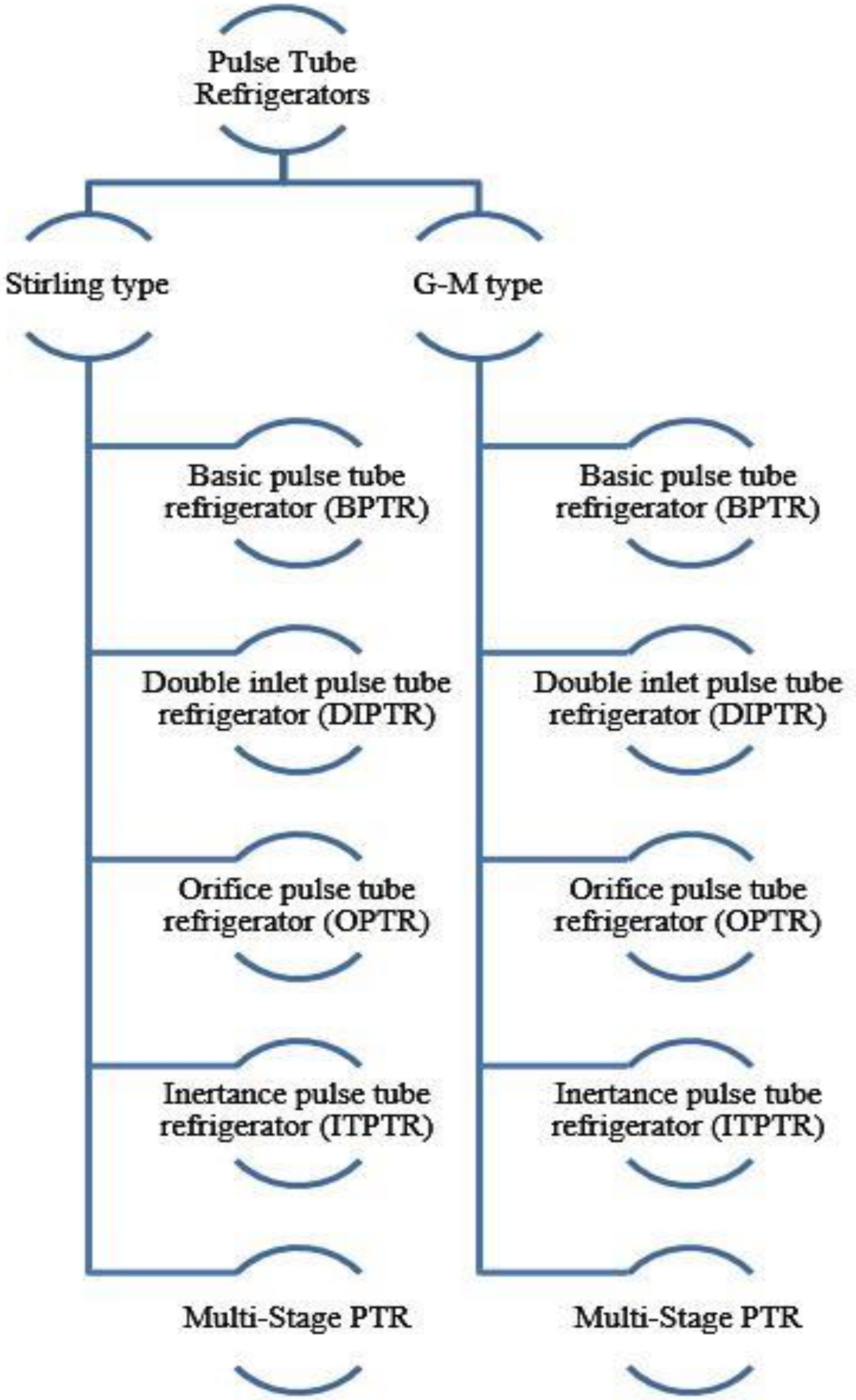
The pulse tube refrigerators (PTR) are competent of cooling to a temperature beneath 100K. The main components of pulse tube refrigerators are a compressor, after cooler, regenerator, cold heat exchanger, pulse tube and hot heat exchanger. In contrast to the normal refrigeration cycles which utilize the vapor compression cycle as described in classical thermodynamics, a PTR implements the idea of oscillatory compression and growth of the gas inside a closed quantity to acquire preferred refrigeration. Being oscillatory, a PTR is an unsteady system that requires time-based result. Nevertheless like many other periodic systems, PTRs accomplish quasi-static periodic state. In a periodic steady state system, the property of the system in a cycle at any factor will reach the same state in the following cycle and so forth. A Pulse tube refrigerator is a closed process that uses an oscillating pressure (typically produced with the aid of an oscillating piston) at one end to generate an oscillating gas flow in the rest of the system. The gas flow goes with the flow can raise warmness away to the hot end heat exchanger from a low-temperature point (cold heat exchanger), if the power factor for the phasor values is favorable. The amount of heat they can get rid of was limited by way of their size and power used to power them.

1.4 Classification of Pulse Tube Refrigerators

Based on nature of pressure wave generator:

(i) Stirling type PTR (valveless)

(ii) Gifford-McMahon (GM) type PTR (with valve)


Pulse Tube Refrigerators
Stirling type
G-M type
Basic pulse tube refrigerator (BPTR)
Double inlet pulse tube refrigerator (DIPTR)
Orifice pulse tube refrigerator (OPTR)
Inertance pulse tube refrigerator (ITPTR)
Multi-Stage PTR
Basic pulse tube refrigerator (BPTR)
Double inlet pulse tube refrigerator (DIPTR)
Orifice pulse tube refrigerator (OPTR)
Inertance pulse tube refrigerator (ITPTR)
Multi-Stage PTR

On the way of development:

(i) Basic Pulse Tube Refrigerator (BPTR)

(ii) Double inlet pulse tube refrigerator (DIPTR)

(iii) Orifice pulse tube refrigerator (OPTR)

(iv) Inertance tube pulse tube refrigerator (ITPTR)

(v) Multiple inlet pulse tube refrigerator

(vi) Thermoacoustic pulse tube refrigerator (TAPTR)

According to geometry or shape:

(i) In-line type pulse tube refrigerator

(ii) U type pulse tube refrigerator

(iii) Coaxial type pulse tube refrigerator

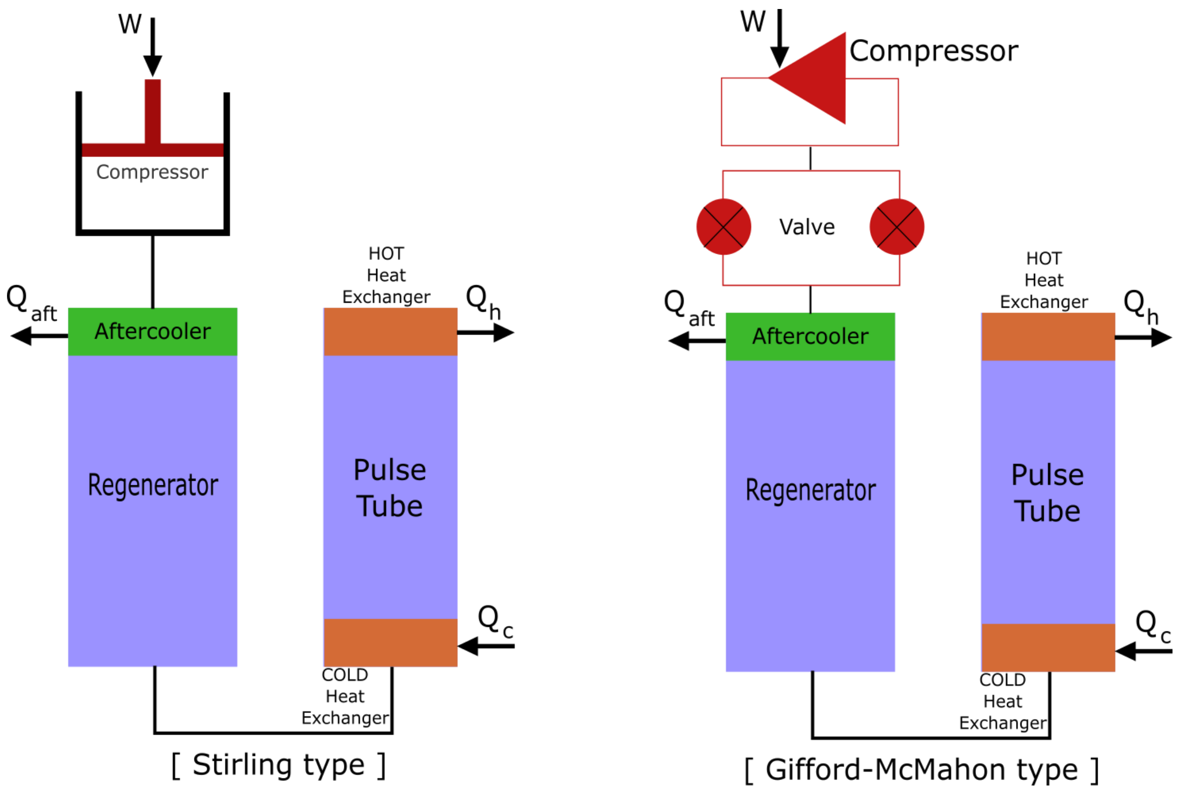


Fig: 1.1 Schematics of basic pulse tube refrigerator (a) Stirling type (b) G-M type.

1.5 Components of Pulse Tube Refrigerator:

❖ Compressor:

Compressor is the main component in a pulse tube cryocooler. The pressurization and depressurization required in a pulse tuber cryocooler is done by the compressor. Based on the capacity and requirement compressors are used usually reciprocating type compressors are used. The electrical energy supplied to the compressor gets converted to mechanical energy which in turn results in pressure wave generation, more particularly it generates sinusoidal type. From the compressor pure cryogenic gas is supplied to the pulse tube cryocooler for further operation. There must be a pressure ratio which is to be maintained across the pulse tube cryocooler.

After cooler:

After cooler is used to extract the entire heat that is generated in the compressor volume during the gas compression and spread to the environment. This minimizes the warm end temperature so that the regenerator can work more effectively and deliver low temperature working fluid to the process. Most often, these varieties of heat exchangers are assembled utilizing copper wire mesh screens which are directly in touch with the housing wall.

❖ Regenerator:

Regenerator is the heart of pulse tube cryocooler. After the compressed gas passes through the after cooler it goes through the regenerator. In this forward stroke the heat of the gas is taken by the matrix of the regenerator. And during depressurization the heat gets transferred to the cold gas from the same matrix present in the pulse tube cryocooler. So very good thermal conductivity material is usually used in the pulse tube cryocooler.

❖ Cold Heat Exchanger (CHX):

CHX can be best seen in what might as well be called the evaporator in the vapor compression refrigeration cycle. It is the place where the system consumes the refrigeration load. It is the link between the regenerator and pulse tube. Copper wire mesh screens are utilized to exchange heat with the housing wall, and in this way get the connected heat load.

❖ Pulse Tube:

The pulse tube is the most basic segment of the entire refrigerating system. The fundamental intention of the pulse tube is to convey the heat from the cold end to the warm end by an enthalpy stream. By forcing a correct phase difference amongst pressure and mass flow in the pulse tube by phase shifting mechanisms, the heat load is conveyed from the CHX to the WHX. Physically, the pulse tube is a hollow cylindrical tube made up of stainless steel with an optimum thickness to boost the surface heat pumping.

❖ Hot Heat Exchanger (HHX):

The gas rejects heat of compression in every periodic cycle of operation in hot heat exchanger. After getting the enthalpy flow from the pulse tube, the heat load at a higher temperature is rejected to the environment. Mostly, air cooling or water cooling system is utilized to take away the heat from the hot heat exchanger.

❖ Inertance Tube:

The part of the inertance tube is suitable to alter the phase difference between the mass flow rate and the pressure. By controlling the inertance tube diameter and length, the craved stage relationship can be acquired. In general, the inertance tube is an open cylindrical stainless tube. In correlation with the previously stated pulse tube, the inertance tube is much longer, and its diameter is much smaller.

❖ Surge Volume:

The surge volume is a closed buffer reservoir of adequate volume to allow for small pressure deviations resulting from the oscillating mass flow.

1.6.1 Basic Pulse Tube Refrigerators (BPTR):

BPTR has oscillatory pressure waves which enforce a shuttling outcome to the working fluid in the pulse tube. Thus there is an energy interaction between the working fluid and the pulse tube wall. It is known as surface heat pumping process. Thus, the BPTR achieves refrigeration through the surface heat pumping process between the pulse tube walls and the working fluid. BPTRs have relatively low coefficients of performance. In this there is no hot mass flow rate as the gas does not leave the hot end. That is the mass flow rate at the hot end is zero.

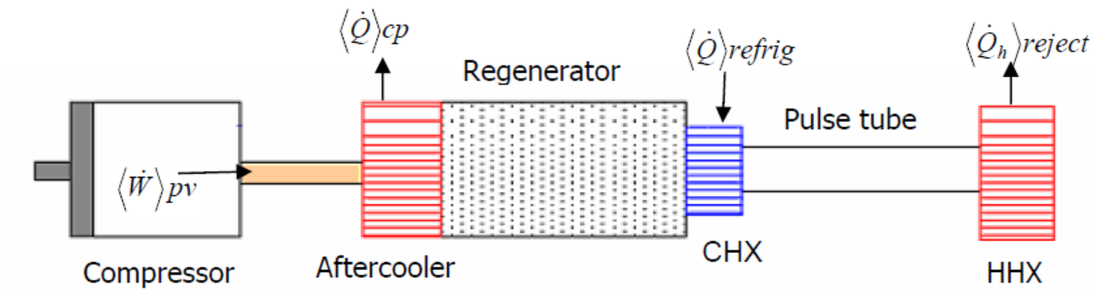


Fig: 1.2 Schematic diagram of basic pulse tube refrigerator

1.6.2 Inertance Tube Pulse Tube Refrigerators (ITPTR):

The inertance tube pulse tube refrigerator is the most recently invented PTR. Inertance means inertia and inductance. It means the mass flow rate is through inductive circuit or where impedance to flow rate occours in a tube.It adds reactive impedance to the system. The execution of this inductance creates a valuable phase shift in pulse tube and generates an improved flow of enthalpy. Studies show that use of the inertance tube is beneficial for large-scale pulse tubes operating at higher frequencies.

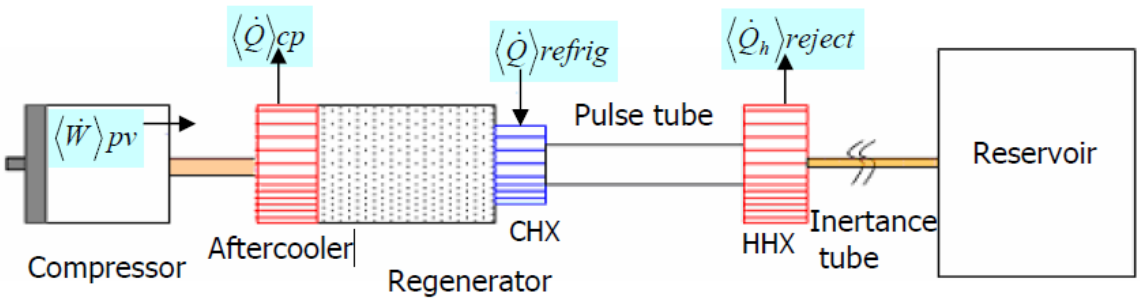


Fig: 1.3 Schematic diagram of ITPTR

1.7 Aims & Objectives:

All pulse tube refrigerator units operate on closed systems where no mass is replaced between the cryocooler and the environment. Mostly, helium is chosen as working fluid because it offers the lowest critical temperature compared to other available gas and having high thermal conductivity. The only moving component is the piston which oscillates back and forth to create periodic pressure oscillation of the working fluid. Accurate sculpting of the pulse tube cryocooler is vital to predicting its performance. The complexity of the periodic flow in the PTC makes analysis difficult. The computational fluid dynamics (CFD) software is used modeling of transient flow and heat transfer process in complex geometries for the analysis of PTRs. The experimental method to evaluate the optimum parameters of PTRs is difficult. Therefore, numerical experimentation using CFD-FLUENT software is used.

The objective of my study is to concentrate on the subsequent points:

- The principle of low-temperature generation in pulse tube cryocooler from one-dimensional model.
- The simulation of PTC using CFD- FLUENT software, to study the heat transfer characteristics and the flow phenomena in the pulse tube system. Under this simulation, 2D -contour axis-symmetric problem of Stirling type inertance pulse tube is analyzed.

1.8 Organization of the Thesis:

The thesis contains six chapters including the present chapter. In this chapter, an introduction about cryocoolers, its classification, working principles and general applications are discussed. A brief description of the basic and inertance type of pulse tube refrigerators along with their components are discussed. The second chapter deals with a review of the literature on pulse tube refrigerators and its operation principles. The third chapter describes the CFD simulation procedures of PTR. It included geometry creation, mesh generation, fluent set up, defining boundary and operating conditions. The fourth chapter describes the fluent analysis of ITPTR. Dynamic meshing function is explained in this chapter. Detailed FLUENT simulation results are discussed with contour diagrams and plots in the fifth chapter. In the last chapter, concluding remarks on the results and some recommendations have also been highlighted for further investigation.

Chapter 2

Literature Review

2.1 Prologue:

Scientist Longsworth and Gifford from University of Syracuse started the pulse tube refrigerator to get low temperature. In 1964, a newest paper [1] of it was published. According to their findings the method 'Pressurization and depressurization of any closed volume from a point on its edge set up temperature gradients in the volume' can obtained. From that theory a temperature gradients was obtained by taking suitable boundary operating condition and a closed volume analysis was chosen. At beginning a hollow-cylinder tube was taken and one surface of it exposed closed end. The closed end is maintained at ambient temperature, whereas the open end is used for the cold temperature. An oscillatory flow field is generated by the piston, and triggered so that the open side should exposed to oscillatory pressure that are coming from the regenerator, which again cools the open end. This type of set up is called as 'Basic Pulse Tube Refrigerator' (BPTR).

Longsworth and Gifford [2] has done useful investigation on refrigeration in a pulse tube which operates at pressure ratio which is well below compared to critical pressure ratio. Longsworth and Gifford [3] developed relationship with parameter like the cold end temperature with zero heat pumping rate regarding the ratio of length, temperature at hot end and specific heats ratio of gas with the help of mechanism of surface heat pumping. They concluded that heat pumping effect at surface was due to interface between fluid motion on the surface, exchange of energy in the fluid, and surface heat exchange, because of periodic changes of gas pressure. Same authors [4] stated the possible difficulties in reversible pulse tube and the parameters were compared with valve type pulse tube.

De Boer [5] proposd an efficient a model for BFTR based on thermodynamics, from the model the movement of gas molecules during heating and cooling was observed and the results obtained are more closed to temperature profiles. De Boer again [6] has done some modification with the same thermodynamic model with heat exchanger at cold and hot end. Scientist J.E. Soo [7] analyzed the secondary flow in BPTR. In that era the efficiency is not up to the mark so, the practical usage seems to be very less.

In 1984, Mikulin developed a newer design called as Orifice pulse tube the refrigerator. Radebaugh and Starch [8] developed a model which is to be solved analytically for OPTR and a simple term for the total refrigeration power were proposed. Zhu et al. [9] analyzed numerically for OPTR considering compressor . Richardson [10] made it possible to decrease its temperature significantly. Lee et al. [12] gave the theory on effect of gas velocity on the surface heat pumping for OPTR. Tward et al. [11] gave some theory regarding the operation of pulse tube coolers to evaluate their rightness for the growth of long life space coolers. Performance and characteristics of OPTR was analyzed numerically by Wang et al. [14]. Kasuya et al. [13] have analyzed optimum phase angle between gas displacement and pressure in pulse tube refrigerator. At NASA–Ames Research Centre Kittel [15] tried to find optimization of the thermal regenerator and pressure wave generator to improve the functioning. David et al. [16] proposed the theory relating to evaluation of heat flow behavior through a pulse tube. Cha and Ghiaasiaan [17] studied two pulse tube refrigerator of inertance tube type having taking a set of dimensions for compressor, after-cooler, regenerator, CHX, pulse tube, HHX with more than one case with different boundary conditions ,the set up were run for simulation. It was found that for one dimension flow model, it seems that greater length-to-diameter ratio and for multi-dimensional flow changes suddenly at the junction of two components, and another flow circulation formed where length divided by diameter is small. Ashwin et al., [18] focuses on the working Pulse Tube Refrigerator of inductance type and the Orifice Pulse Tube Refrigerator having an inline and co-axial configuration. Simulation work has done considering the fluid flow and heat transfer, with changing length-to-diameter ratios. Porous medium has been chosen for heat exchanger and regenerator, and through them temperature gradient applied. The result showed that non-thermal equilibrium analysis yields a lower cold heat exchanger temperature. Ling et al, [19] simulated a pulse tube for the analysis of thermal cycle. It showed that the different thermodynamic processes took place when the gas pass from the ITPTR components. It was found that materials working on different frequency but the component is same than the thermodynamic results were approximately ssame.

Gardner et al. [21] gave a new way of using an inertance tube in place of orifice valve. They proposed and done some calculation on phase shift between velocity and oscillating pressure and found that by using that with the use of inertance tube efficiency of cooling power increases. Roach et al. [22] found the advantages gained by the use of an inertance tube in a pulse tube cooler, which provides additional phase shift between mass flow rate and pressure in the pulse tube section. De Boer [23] calculated the refrigeration rate for an inertance pulse tube cryocooler as a function of the relevant parameters in the obvious case of zero dead volume of the regenerator and infinite volume of the reservoir. The ITPTR is more efficient compare to that of the OPTR over a partial range of frequencies.

Zhu et. al. [24] gave nodal analysis method for simulating inertance tube pulse tube refrigerators .Wei et al. [25] has done theoretical calculation for a inertance tube without a reservoir and found that it gives a large phase-leading result. Based on results a larger void volume of pulse tube requires larger phase-leading effect. So , phasor diagram is used to analyze the relationship between phase-leading requirement and the geometry of pulse tube.

2.2. Methodology:

2.2.1 Pulses Tube Refrigerators Process Code:

The process principle of PTR is synonymous to the general refrigeration systems, but method of eliminating heat is little bit different. The cycle of vapor compression cycle in figure 2.1 process in a steady flow system in which heat is transferred from the evaporator to the condenser through a constant and steady flow rate of mass. The PTR depend on an oscillatory pressure wave in the organism for extracting heat from the chx to hhx.

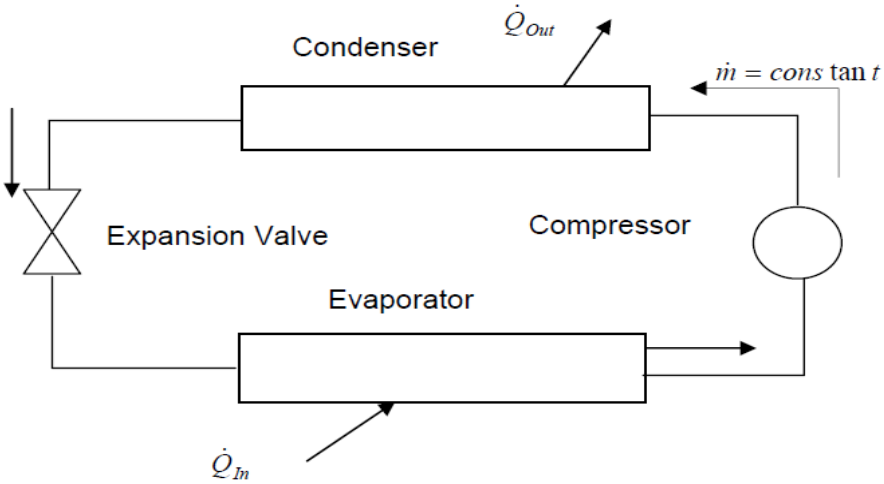


Fig: 2.1 Schematic diagram of the simple vapor compression cycle

In the pulse tube refrigerator, the cooling occurs in the oscillating pressure environment. The heat is sucked up and eliminated between two heat exchangers. It is a cyclic process. Because PTR operates in a steady-periodic mode, the thermodynamic properties such as enthalpy flow $\langle \dot{H} \rangle$, heat flow $\langle \dot{Q} \rangle$ and power $\langle \dot{W} \rangle$ are evaluated in the form of cyclic integrals. The suitable instantaneous thermodynamic properties are integrated over the entire cycle and separated by the period of that cycle to obtain the cyclic averaged value of it. For example, the compressor power is evaluated from the following integration.

$$\langle \dot{W} \rangle_{PV} = f \oint P \frac{dV}{dt} dt = \frac{1}{\varsigma} \oint P(t) \dot{V}(t) dt \qquad (2.1)$$

Where ς is period of the cycle, f is frequency, V and P are instantaneous pressure and volume respectively. The average enthalpy flow over one cycle $\langle \dot{H} \rangle$ and average heat flow rate $\langle \dot{Q} \rangle$, are also calculated similarly.

2.2.2 Governing Equations for Pulse Tube Refrigerator:

The PTR system mainly consists of a dual opposed piston compressor, a transfer line, an after cooler, regenerator, pulse tube, cold end heat exchanger (CHX), inertance tube, hot end heat exchanger (HHX), and a reservoir. Continuum-based conservation equations can be applied everywhere in the system. This is appropriate since the mean free path of a gas molecule is typically much smaller than the characteristic dimension of the system components. Continuum based conservation of mass, momentum, energy equations solved by Fluent for the upcoming simulations are, respectively.

$$\frac{\partial \rho_f}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\rho_f v_r\right]+\frac{\partial}{\partial x}\left[\rho_f v_x\right]=0 \tag{2.2}$$

$$\frac{\partial}{\partial t}\left[\rho_f \vec{v}\right]+\nabla\cdot\left[\rho_f \vec{v}\vec{v}\right]=-\nabla p+\nabla\cdot\left[\overline{\overline{\tau}}\right] \tag{2.3}$$

$$\frac{\partial}{\partial t}\left[\rho_f E\right]+\nabla\cdot\left[\vec{v}\left(\rho_f E+p\right)\right]=\nabla\cdot\left[k_f \nabla T+\left(\overline{\overline{\tau}}\cdot\vec{v}\right)\right] \tag{2.4}$$

Where,

$$E=h-\frac{p}{\rho}+\frac{v^2}{2} \tag{2.5}$$

The above equations employ to all components, except for the aftercooler, the regenerator, cold and hot heat exchanger. These four constituents are exhibited as porous-media, adopting that there is local thermo stability of the fluid with the solid construction in the components. The mass, momentum, and energy equations for these four components were as follows:

$$\frac{\partial}{\partial t}\left[\varepsilon\rho_f\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[\varepsilon r\rho_f v_r\right]+\frac{\partial}{\partial x}\left[\varepsilon\rho_f v_x\right]=0 \tag{2.6}$$

$$\frac{\partial}{\partial t}\left[\varepsilon\rho_f\vec{v}\right]+\nabla\cdot\left[\varepsilon\rho_f\vec{v}\vec{v}\right]=-\varepsilon\nabla p+\nabla\cdot\left[\varepsilon\overline{\overline{\tau}}\right]-\left[\mu\overline{\overline{\beta}}^{-1}\cdot\vec{j}+\frac{1}{2}\overline{\overline{C}}\rho_f\cdot\left|\vec{j}\right|\vec{j}\right] \tag{2.7}$$

$$\frac{\partial}{\partial t}\left[\varepsilon\rho_f E_f+(1-\varepsilon)\rho_s E_s\right]+\nabla\cdot\left[\vec{v}(\rho_f E_f+p\right]=\nabla\cdot\left[(\varepsilon k_f+(1-\varepsilon)k_s)\nabla T+(\varepsilon\overline{\overline{\tau}}\cdot\vec{v})\right] \tag{2.8}$$

Where $\varepsilon=0.69$, $\overline{\overline{\beta}}=1.06\times10^{-10}m^2$, and $\overline{\overline{C}}=7.609\times10^4 m^{-1}$ were assumed. These parameters are based on the experiments of Harvey [20].

Chapter 3

CFD Simulation Procedure

3.1 **Finite Volume Method (FVM):**

To explain the governing equation of the flud flow and transfer of heat problems, finite volume method is used. Exact integral balances are shown by use of coarse grid. We can try any grids (fine or coarse, unstructured or structured, Cartesian) also to complex geometries. In FVM, the domain of the solution is further divided into some continuous cells or the control volumes that variable is placed on centroid of control volume which form grid. Then the governing equation which is in differential form is integrated on all control volume. Different types of patterns are used for interpolation like upwind, quadratic, power-law and central type of differencing methods. It is known as discretized equation.

3.2 Geometry Creation:

Heating and fluid flowing in the refrigeration system of pulse tube are designed by Fluent 15 version. Initially, a proper geometry is to be created. After getting the dimensions of all the components of PTR, the geometry is used to create the faces. The 2-D design is made to create ITPTR. All faces were united after that and 'split-zoned' function is used to declare boundary conditions on each zones. As the computational geometry is Axis-symmetric in the latest case, so only the one half of the geometry is considered for experimental analysis.

3.3 Mesh Generation:

To mesh the given 2-D planar geometry, the first step is to create nodes (points where the grid lines of the mesh connect) on the edges. This can be done either by specifying equidistance spacing between the nodes, which provides a uniform mesh, or a gradually increasing /decreasing spacing (boundary layer mesh), which provides a non-uniform mesh with a finer resolution across a certain region in the domain, such as along the bottom and sides walls of the present geometry, to estimate the velocity and temperature gradients accurately near the walls. Once the nodes are created, then one can generate the actual mesh along the faces. Different options for mesh generation are available in Fluent. To list a few are triangular elements, hexahedral elements and quadrilateral elements. The structured quad element is used for meshing.

3.4 Boundary Settings:

The next step is to create zones of boundaries of the geometry which are used afterwards by Fluent to mark the boundary conditions. In the current investigation, each of the top-lines and sidelines of the structure were named as "wall." Wall is defined as the surface which is supposed to be solid and no fluid would penetrate through it.

3.5 Fluent setup:

Initially, the fluent will check the grid for detection of errors. It will make sure that all zones of it are there and have correct dimensions. If there's negative volume detecting, there must be some error in grid as volumes can't be negative.

3.6 Defining the Model:

The model properties are vital to be specified. These properties include the type of fluent solver, the material and thermal properties apart from model operating conditions and grid boundary conditions. The following settings are used to create the model in Fluent.

❖ Solver:

Fluent 15 has three different solver formulations, i.e. segregated, coupled implicit, and coupled explicitly. In the segregated solver approach, the governing equations are solved sequentially (i.e. an equation for a certain variable is solved for all cells, and then the equation for the next variable is solved for all cells). The segregated solution method is best suited for incompressible flows or compressible flows at low Mach number. In the present study *segregated solver with implicit formulation* has been used.

For this study, the options chosen for Stirling type ITPTR are as follows:

- Flow Model:2D Axisymmetric, Unsteady, turbulent flow
- Solver: Segregated, Double Precision
- Unsteady Formulation: Second order Implicit
- Porous Formulation: Physical velocity

❖ Energy:

It enables energy equation in the solver for solving heat transfer problem. Accordingly, energy option is enabled.

3.7 Defining the Material Properties:

In this experiment, analysis fluid is helium and solid are steel and copper. Some properties are specified in that section like specific heat, thermal conductivity, density,viscosity and diffusivity.

3.8 Describing the Operating Conditions:

The operating condition has gravity consideration and pressure. The gravity effect is considered. Operating pressure is set at 35 bars.

3.9 Defining the Porous Zone:

The regenerator, after cooler, cold end heat exchanger and hot end exchanger of a pulse tube refrigerator is to be modeled using porous media methods. A porous zone is modeled as a special type of fluid zone. To indicate that the fluid zone is a porous region, porous zone option in the fluid panel is enabled. The panel expands to show the porous media inputs. The user inputs for porous media model are:

- Define the porous zone.
- Identify the fluid material flowing through the porous media.
- Select the solid material contained in the porous media.
- Specify the porosity of the porous media.
- Set the viscous resistance coefficients and inertial resistance coefficients, and define the direction vectors for which they apply.

3.10 Executing the Fluent CFD code:

The PRESTO (Pressured Staggering Option) is used for obtaining the pressure values and PISO (Pressure Implicit with Splitting of Operators) is used to couple the interaction between pressure and velocity. A line by line solver based on the TDMA (Tri-diagonal matrix algorithm) is used to iteratively solve the algebraic equations obtained after discretization. Proper under relaxation factors are used for the solution of the pressure correction equation, the two momentum equations and the energy equation respectively.

3.12 Solution Initialization:

Each case must be initialized before the fluent code begins iterating towards a converged solution. Initializing the case essentially provides an initial guess for the first iteration of the solution. In the initialization process, the user must specify which zone is be provided with initial condition. Different model properties viz. continuity, x-velocity, y-velocity, energy, k and ε were monitored by fluent solver and checked for convergence. This criterion requires that the scaled residuals decrease to 10^{-3} for all equations except the energy equation, where the criterion is 10^{-6}. At the end of each solver iteration, the residual sum for each of the conserved variables is computed and stored. Thus it records the convergence history. Table4.3 shows the list of variables at their respective convergence criteria used in the present model.

Table: 3.1 Variables and respective convergence Criteria used in the simulation:

Variable	Convergence Criterion
Continuity	0.001
X-velocity	0.001
Y-velocity	0.001
Z-velocity	0.001
Energy	1e-06
k	0.001
ε	0.001

Once all the above-mentioned steps are over, iteration can be initiated with the time-step of 7.3529×10^{-4} second and number of iterations per time step to be 20.

Chapter 4

CFD Analysis of Stirling Type ITPTR

4.1 Introduction:

Computational fluid dynamics is the investigation of schemes relating stream of the fluid, heat transfer and related occurrence like chemical reactions with the help of numerical recreations. Fluent is used for sculpting fluid flow & heat transfer process in difficult engineering difficulties. We can create codes and fixed boundary condition with the help of UDF. An important function of fluent is dynamic meshing, which permits the user to form distorting mesh volumes in a way that problems concerning volume compression and expansion could be exhibited. Thus, its competency for explaining the .compression and expansion volume, creating UDF edge conditions and modeling capability for porous media, it is chosen for the simulation of the Inertance tube PTR.

Geometry & boundary conditions of ITPTR have been given in details in the following chapter. The basic parameters required here are their dimensions and boundary conditions. Detailed magnitudes of the Stirling type inertance tube PTR are taken from the literature *Cha et al.* and a dual opposed piston model is taken in place of the compressor in the current simulation. Figure: 4.1 displays the 3-D view of the inertance tube pulse tube refrigerator systems. Likewise fig.4.3 demonstrates the 2-D physical geometry of the ITPTR. Figure: 4.1 displays that each element of its system is cylindrical in figure and each components is allied in series to make an axis-symmetric system. The ITPTC is therefore sculpted in a 2D axis-symmetric co - ordinate system. Figure: 4.2 displays the geometry of ITPTR.

Initially, a concrete physical drawing of the system is made as a single component in 2-D and is named in different zones. The main reason of naming the geometry to different components is to assign different boundary conditions to the zones as required. Figure: 4.4 displays the enlarged axis-symmetric geometry of the altered segments of the ITPTR with whole meshing. After the geometries are formed, the model boundaries have to be defined.

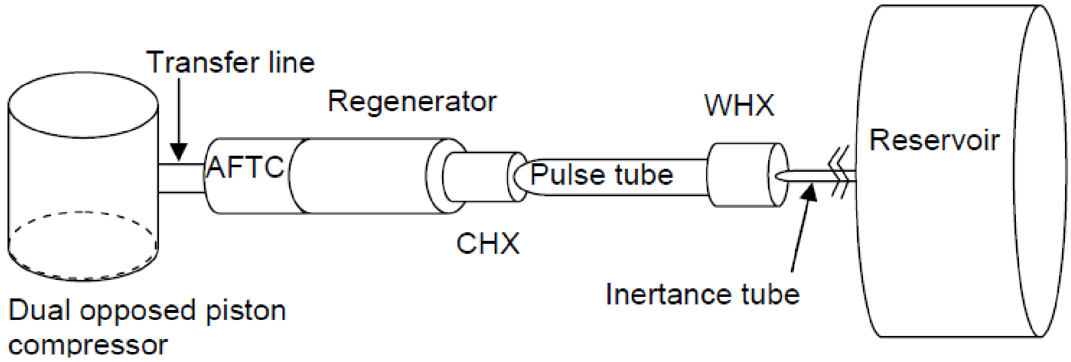


Fig: 4.1 3-D view of the inertance tube pulse tube refrigerator.

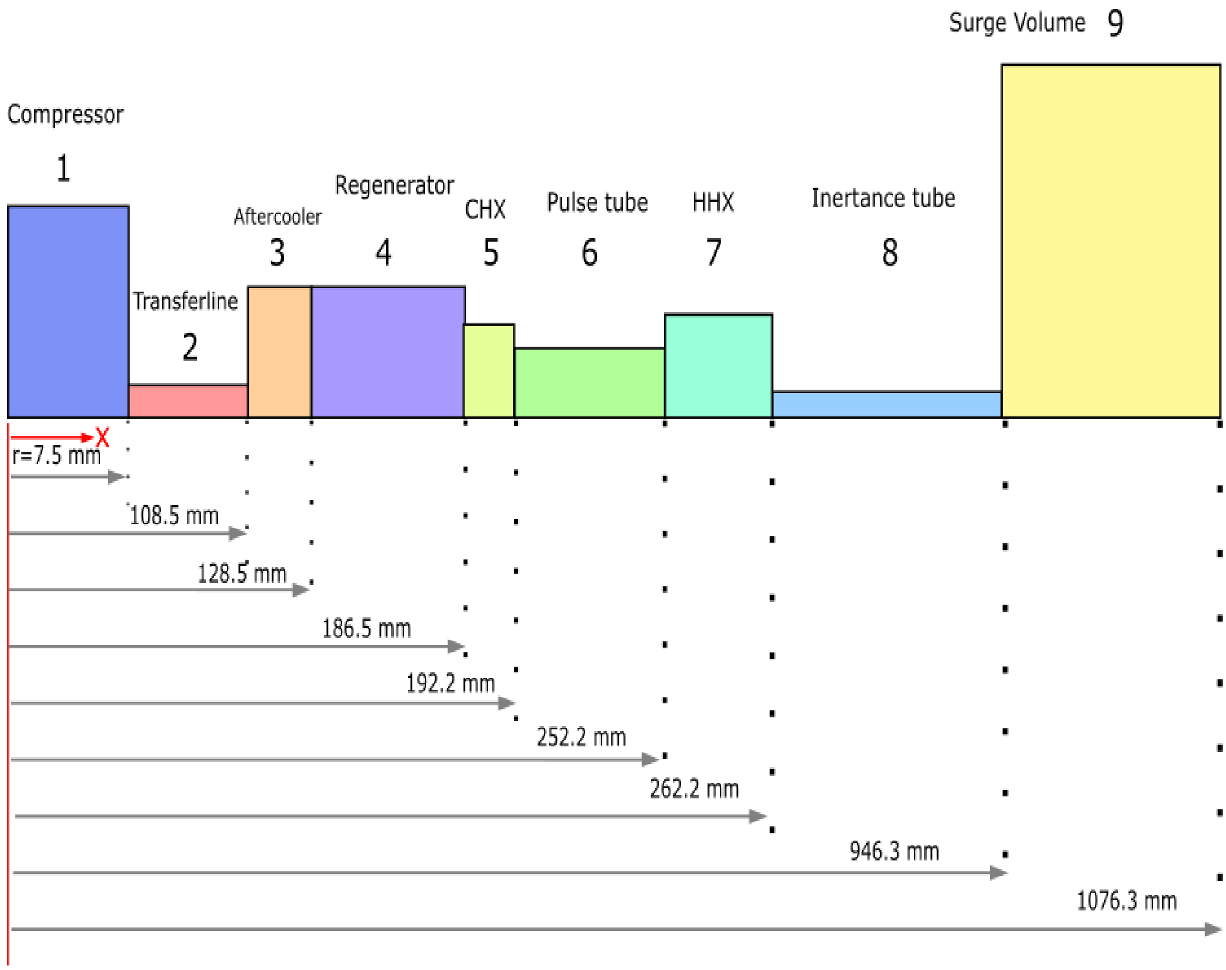


Fig: 4.2 2-D axis-symmetric geometry of inertance tube pulse tube refrigerator.

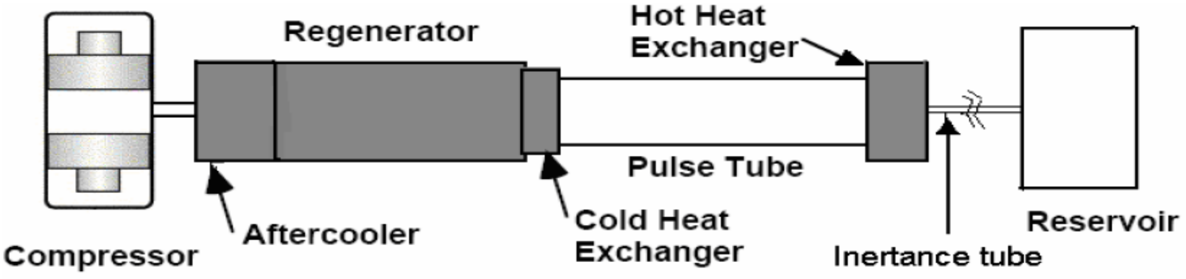
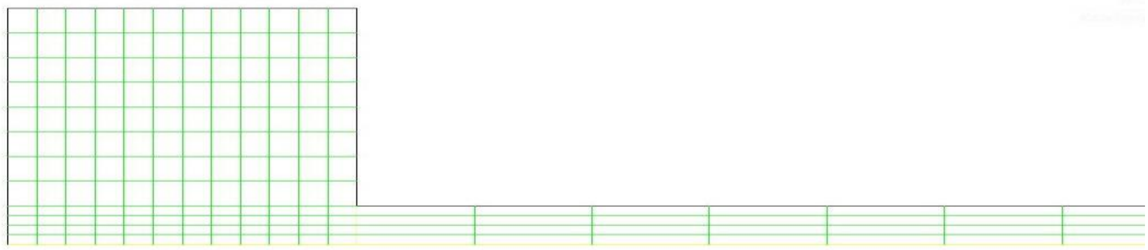
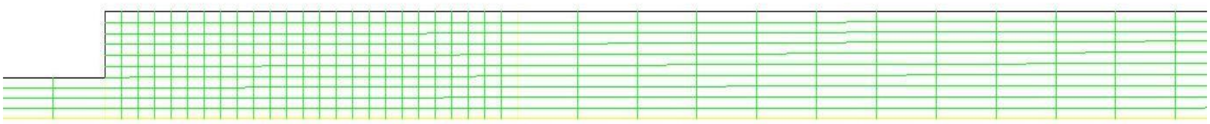
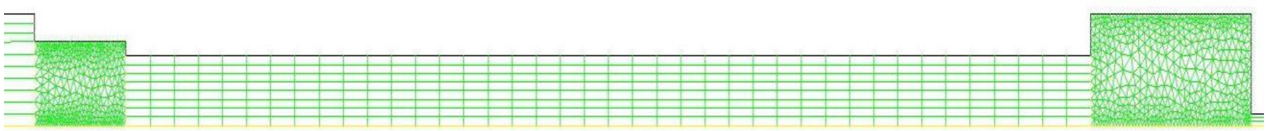


Fig: 4.3 2-D view of inertance tube pulse tube refrigerator.







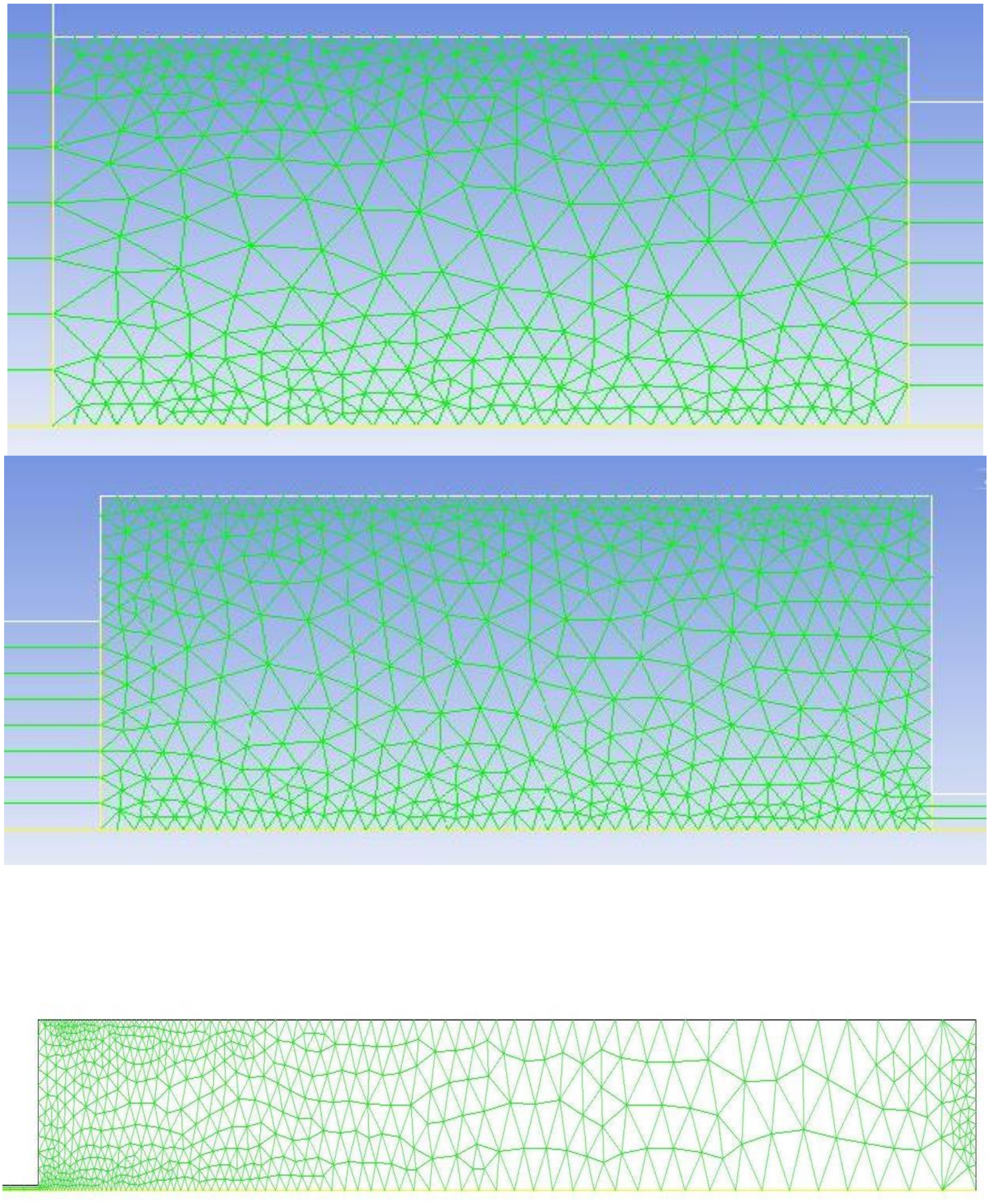


Fig: 4.4 2-D axis-symmetric mesh of ITPTR .

4.3 Dynamic Meshing Function:

The dynamic mesh model is utilized in Fluent to show the flow in which the state of the area is altering with time because of movement in the field boundaries corresponding in the reciprocating compressor when the piston moves the area of fluid. This sort of model could be taken care of in familiar by utilizing dynamic meshing function. The movement could be an endorsed movement or a un-prescribed movement where the ensuing movement is resolved based on the solution at the recent time. The redesign of the cross volume section is taken care of consequently by familiar at every time step bearing in account the new places of the limits. To utilize the dynamic mesh model, it was expected to give an initial volume mesh and the portrayal of the movement utilizing either boundary profiles or user-defined functions. The compressor has been displayed utilizing dynamic meshing as part of ITPTR.

In Fluent, diverse technique is accessible by mesh upgrade like smoothing, layering and remeshing for element fitting. The compressor is demonstrated as a solid wall (piston) in sinusoidal sways in and out lengthwise a constant stroke length. The cylinder and piston walls are apparently indicated as adiabatic boundary. Work given at the piston in a cylinder of a compressor gives the oscillating pressure that runs the cycle. To design the piston and cylinder, fluent dynamic meshing function is utilized. A user-defined function (UDF) is created in C programming dialect to simulate the piston cylinder effect. The compressor developed in that simulation is a reciprocating dual opposed piston. The piston head motion is found in the same way from the accompanying conditions:

Piston displacement is shown as,

$$X = X_a \sin(\omega t)$$

Where $X_a = 4.511\times10^{-3} m$, $\omega = 213.62 rad/s$, $t = 7.3529\times10^{-4} s$ were assumed.

For all cases, the charging pressure is 35 bar and frequency is 20 Hz. Exploration-grade *helium* is taken as the working fluid, displayed as a perfect gas with a constant viscosity, heat capacitance and thermal conductivity. Table: 5.3 demonstrates the boundary conditions of model. In porous regions, the momentum transfer equations incorporate a generated term with inertial & viscous resistance coefficient that had been indicated. After the boundaries are characterized, the solver and the flow features were itemized in Fluent. A segregated solver is utilized on all the models and the job of the solver is to find out the flow and energy equation independently & certainly.

Piston displacement is expressed as,

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For all cases, the charging pressure is 35 bar and frequency is 20 Hz. Exploration-grade helium is taken as the working fluid, displayed as a perfect gas and with a constant viscosity, heat capacitance, and thermal conductivity. Table 5.3 demonstrates the boundary conditions of model. In porous regions, the momentum transport equations incorporate a source term with inertial and viscous resistance coefficient which has been indicated. After the boundaries are characterized, the solver and flow features are itemized in Fluent. A segregated solver is utilized on all models. The job of the solver is to find out the flow and energy equation independently & certainly.

4.4 User-defined function (UDF):

The dynamic mesh of the fluent are used to model the compressor. C programming language is used to make the velocity user defined function (UDF) and is stored by writing a appropriate name like **"piston.c".** It is put away in that folder where the mesh file is spared. UDF in fluent should be compiled and after that it should be connected with a cylinder which creates the reciprocating movement conceivable on the piston. The velocity UDF for piston head movement is as per the following.

```
#include "udf.h"
DEFINE_CG_MOTION(vel_comp,dt,vel,omega,time,dtime)
{
real freq = 34.0;
real w = 2.0 * M_PI * freq;
real Xcomp = 0.0045;
NV_S(vel, = ,0.0);
NV_S(omega, = ,0.0);
vel[1] = w * Xcomp * cos (w * time);
}
```

4.4 Compiling User-defined functions (UDF):

The first step for the compilatio of the UDF is to click i. Defined ii. User-defined iii. functions iv. compile . After these steps, the compiled UDF panel will come to the screen. Then we need to select one proper path and will select 'piston.c' and then click 'ok'. Then click the 'load' button and it will compile the UDF library. The next step is to activate dynamic meshing motion by following steps, i.Define,ii. dynamic mesh ,iii.parameters. Smoothing and layering option is clicked. The last step is click 'Define',then 'dynamic mesh' & 'Zone'. Specify the piston as a rigid body and side walls as deforming here. Then click create and it will link UDF to piston.

4.5 Mesh Motion Preview :

The next step after definig dynamic mesh is to check the mesh movement, whether it is reciprocating appropriately or not. To check the mesh motion, we need to select only the compressor portion of the geometry . The mesh motion screening gives data in regards to the movement of the mesh in either course from their underlying place as for time. It demonstrates the pressure and extension procedure of the compressor . From starting condition network shifts in upward course achieves TDC and afterward goes down till BDC . On the off chance that there was not appropriate coordinating between network size dividing and time increase the meshes will not shift. For this situation, familiar will demonstrate an error notification for negative volume. Thus, before beginning the reproduction, it is important to preview the movement of the meshes for the picked grid size .

Table: 4.1 Component dimensions and material used for ITPTR

Serial No.	Components	Radius (mm)	Length (mm)	Material
1	Compressor	9.54	7.5	Steel
2	Transfer Line	1.55	101	Copper
3	After Cooler	4.00	20	Copper
4	Regenerator	4.00	58	Steel
5	Cold Heat Exchanger	3.00	5.7	Copper
6	Pulse Tube	2.50	60	Steel
7	Hot Heat Exchanger	4.00	10	Copper
8	Inertance Tube	0.425	684.1	Steel
9	Surge Volume	13.00	130	Steel

Table: 4.2 Boundary and initial conditions for ITPTR

Study Case	Case-1	Case-2
Compressor Wall	Adiabatic	Adiabatic
Transfer Line Wall	Adiabatic	Adiabatic
After Cooler Wall	293 K	293 K
Regenerator Wall	Adiabatic	Adiabatic
Cold end Wall	Adiabatic	Heat Flux 1W
Pulse Tube Wall	Adiabatic	Adiabatic
Hot end Wall	293 K	293 K
Inertance Tube Wall	Adiabatic	Adiabatic
Reservoir	Adiabatic	Adiabatic
Viscous resistance (m^{-2})	9.44e+9	9.44e+9
Inertial resistance (m^{-1})	76090	76090
Initial Conditions	300K	300K
Cold end load	0	1W
Cold end temperature	**74.8K**	**96.9K**

CHAPTER-5

Results and Discussion:

Computational dynamics of fluid are done for single stage of stirling ITPTR. Two differents boundary conditions are used at cold end heat exchanger : one is adiabatic and second one is heat load of 1W. The other boundary conditions of rest of the components is not altered. Measurement of component with its boundary conditions are placed in table 4.1 & 4.2 respectively. Steady-periodic CFD simulation conclusion is discussed in that section for different boundary conditions at the cold end heat exchanger .

5.1 Case 1:Adiabatic boundary:

It relates by an adiabatic condition at the cool end wall, that is identical to zero cooling power connected to general system. The investigation prompts the least temperature attainable in the pulse tube refrigeration . Simulation is begun by an expected starting temperature of 300 K and proceeded till steady-periodic conditions are reached. Fig.5.1 demonstrates the deviation of the tip temperature of cold end as a time function at the beginning of simulation. It displays that the temperature of walls of the cold side heat exchanger regularly falls by time: till cyclic steadi state condition is touched.

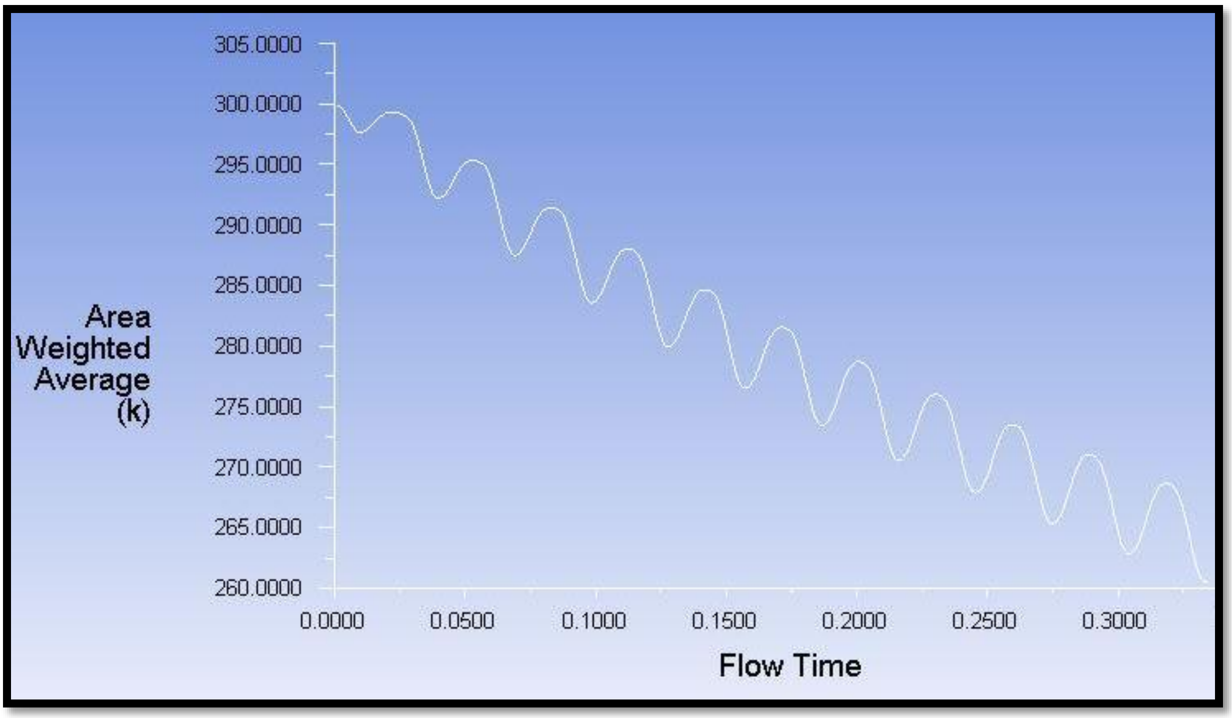

Fig: 5.1 refrigeration behavior at the start of simulation.

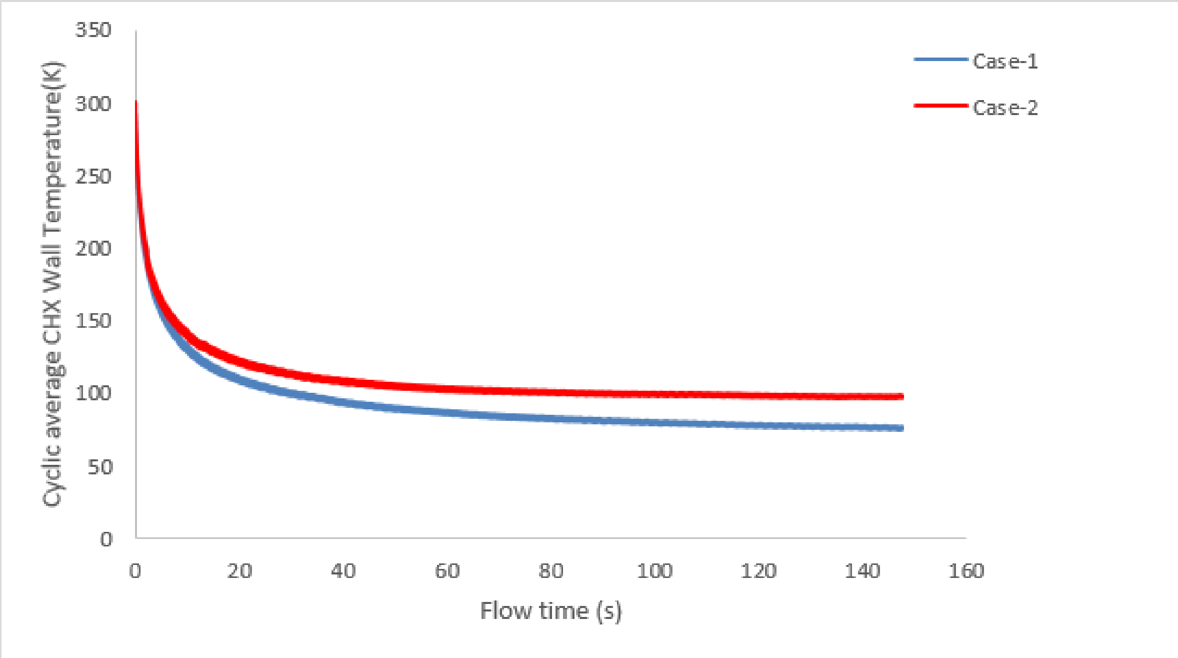

Fig.5.2 cooling behavior till cyclic steady state condition

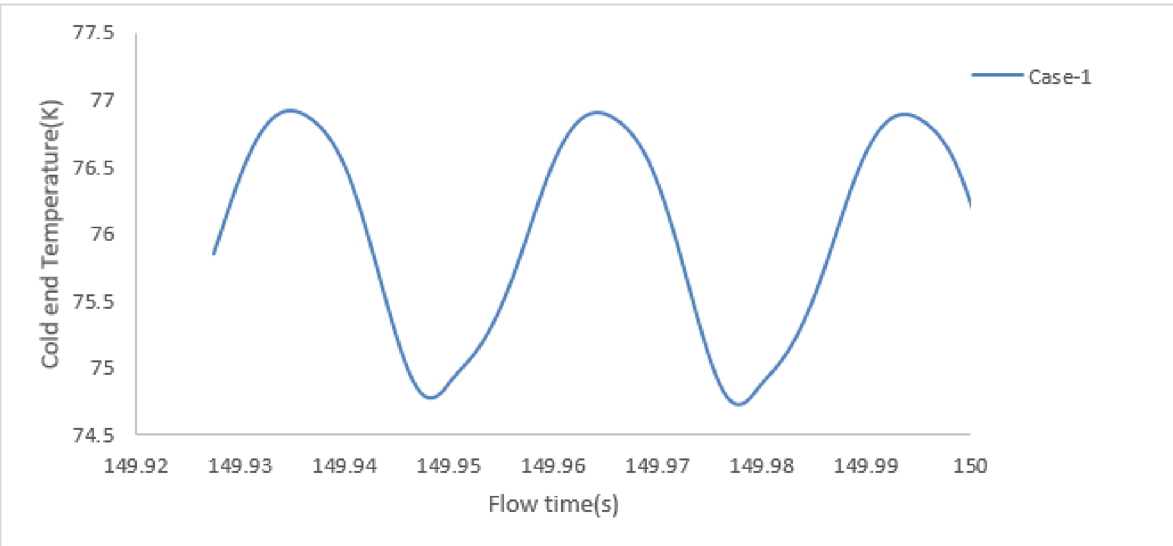

Fig.5.3 CHX wall temperature variation after cyclic steady state condition (case1)

The fig.5.2 displays the steady decline of the cyclic steady state cool down behavior for case:1 & case:2. The least cold side temperature of 74.8 K is attained once taking simulation of 150 seconds for case1. In the described simulation, verification of the steady periodic simulation of the system is done by examining the cold end to check if the temperature of the cold end is identically reiterated from one to the next cycle that is shown in Fig.5.3 and confirms the cyclic steady state condition. Yet, it must be underlined that in real systems, the cooling period will be greater than what is projected in outcome, because the thermal masses is not executed in method.

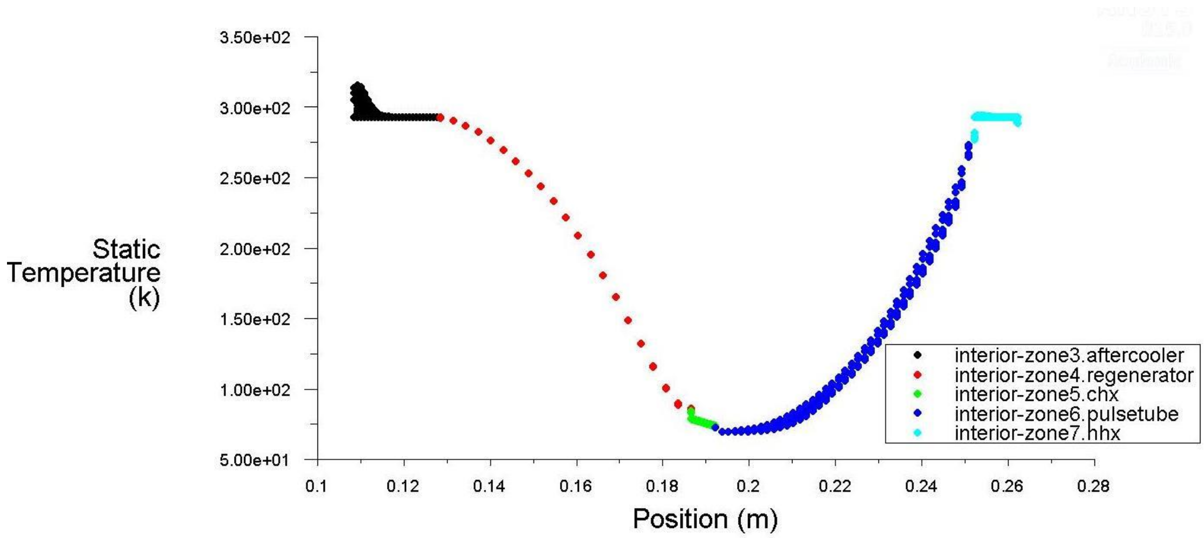

Fig: 5.4 Distributions of Temperature along axial direction for case 1

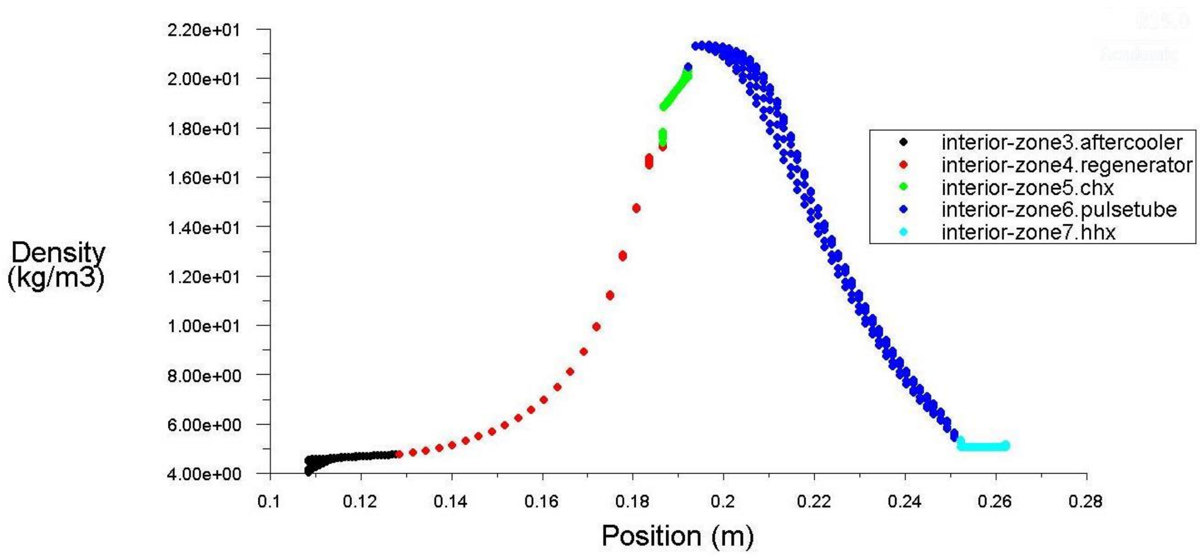

Fig: 5.5 Distributions of Densities along axial direction for case 2

Figures 5.4 and 5.5 showed the temperature and density circulations correspondingly, through the line of whole simulated system. The cyclic average temperature and density profile describe local sudden change of the system. The density sharing trends are regular with the ideal gas equation of state. Figures 5.6 and 5.7 illustrate s the temperature and density contours respectively under steady periodic conditions. The contours are regular with figures 5.4 and 5.5. The Fig. 5.18 shows the velocity vector in the pulse tube, which depicts the smooth flow without swirl in the pulse tube section.

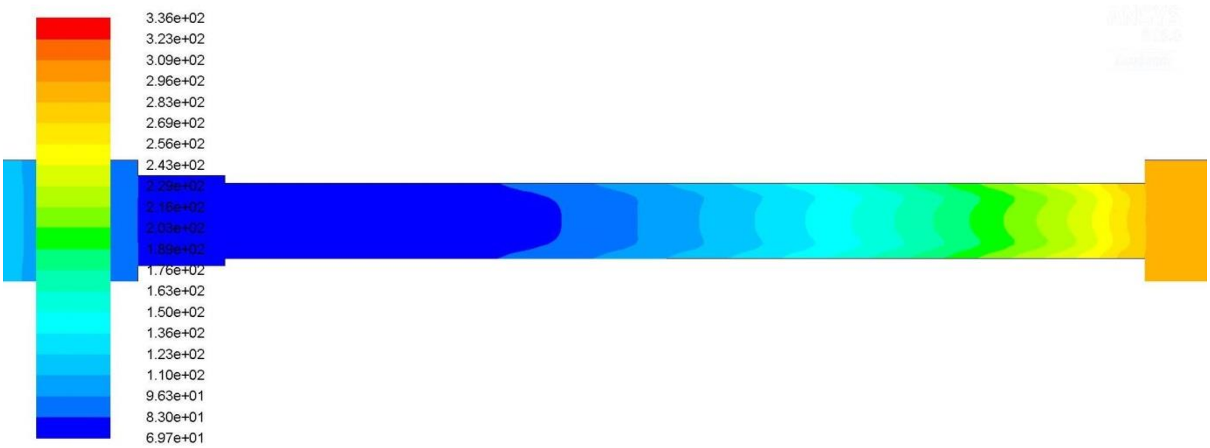

Fig: 5.6 Contours of Temperature for case 1

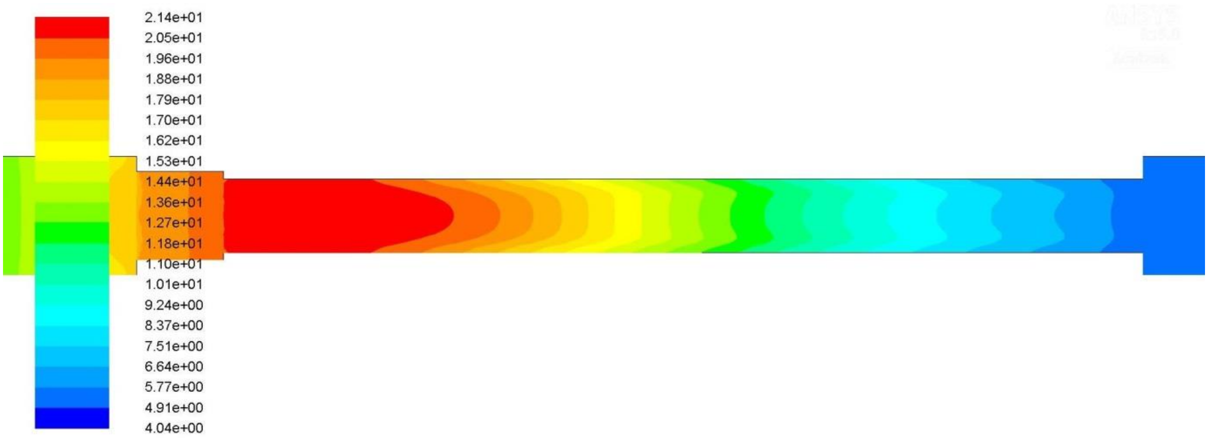

Fig: 5.7 Contours of Densities for case 1

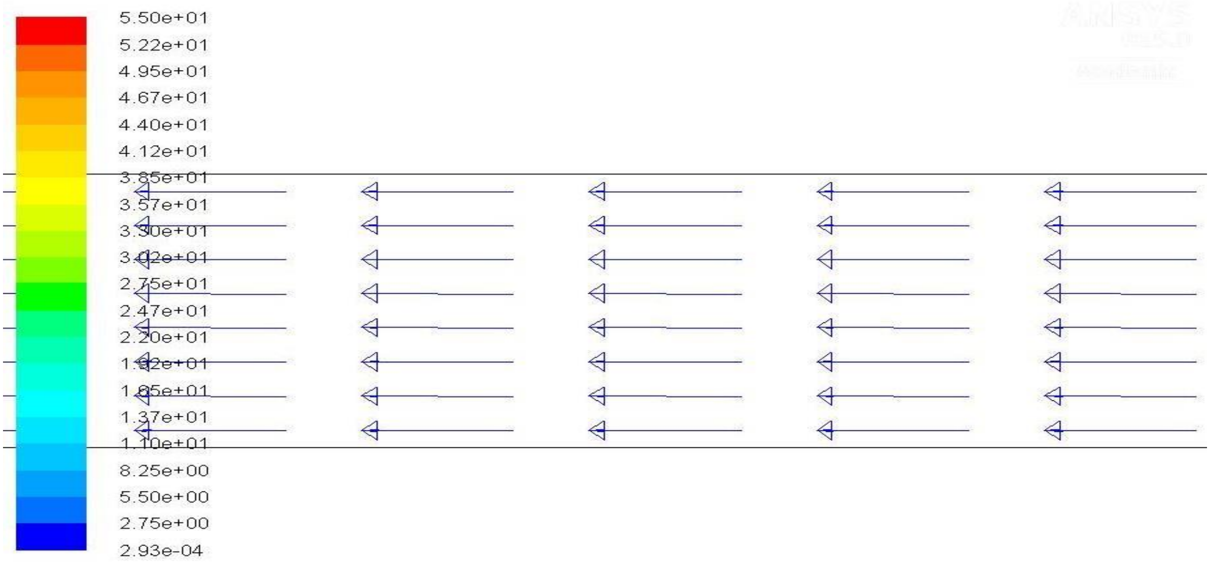

Fig: 5.8 Velocity vector in the pulse tube for case1.

5.2 Case 2: Known Heat Load Boundary Condition:

In this case, the simulation of inertance tube pulse tube with a constant heat load of 1W is shown at the cold end heat exchanger . This is corresponding to the method going for a refrigeration load of 1W. Initial temperature of 300K is assumed initially and is sustained until steady periodic conditions are achieved. Variation of the temperature of cold end with time is displayed in fig.5.2. The simulation showed that the cold end surface temperature of 96.9K is found out from the graph.

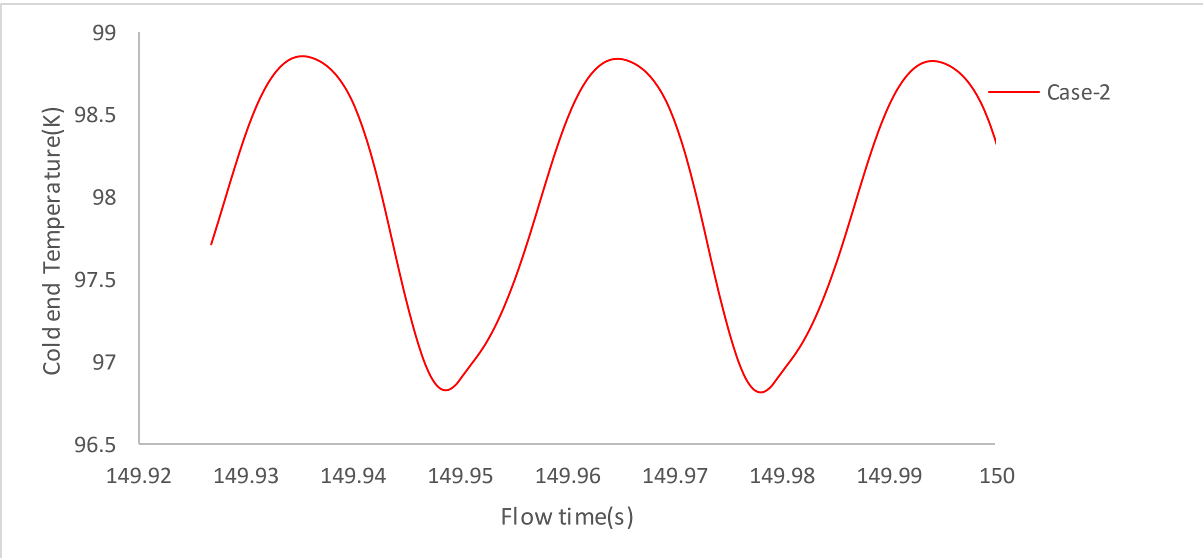

Fig: 5.9 CHX wall temperature variation at cyclic steady state condition (case-2)

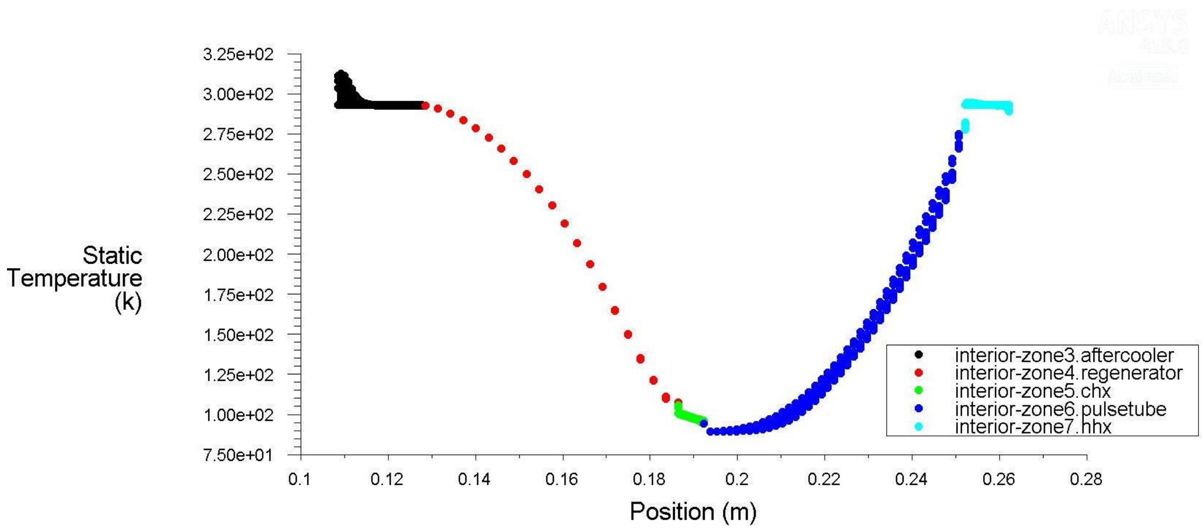

Fig: 5.10 Distributions of Temperature along axial direction for case 2

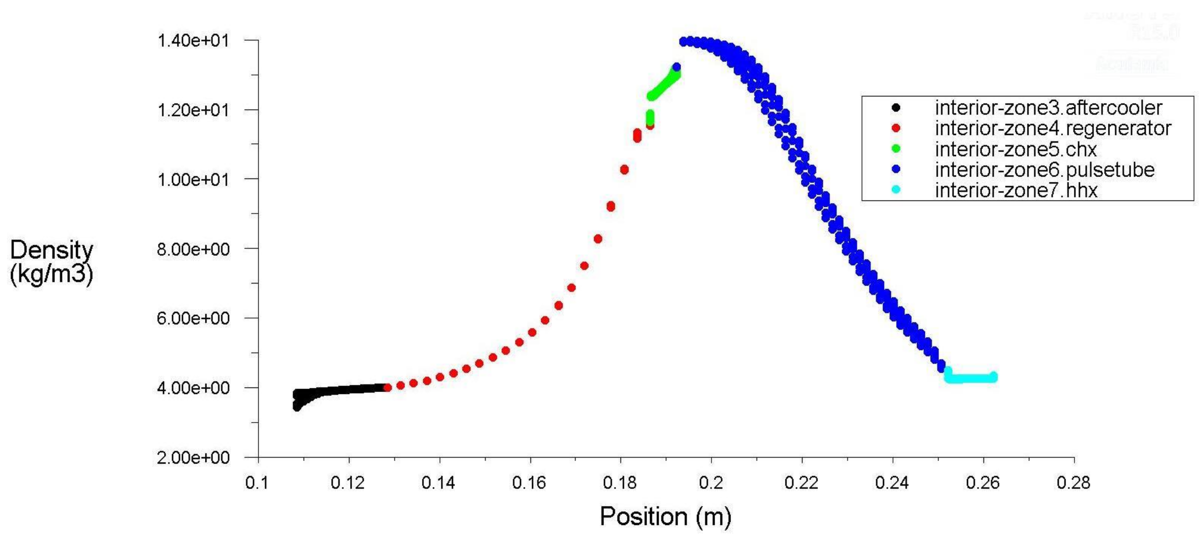

Fig.5.11 Distributions of Density along axial direction for case 2

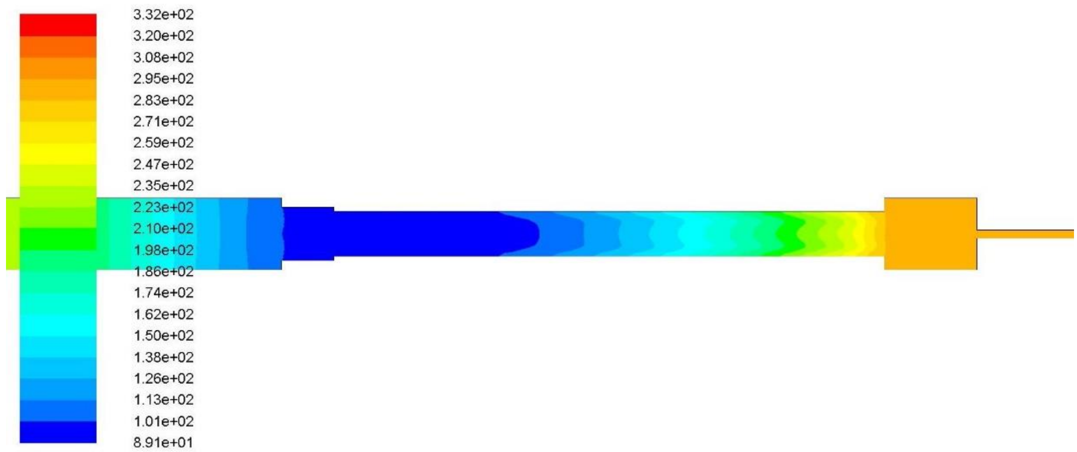

Fig.5.12 Contours of Temperature for case 2

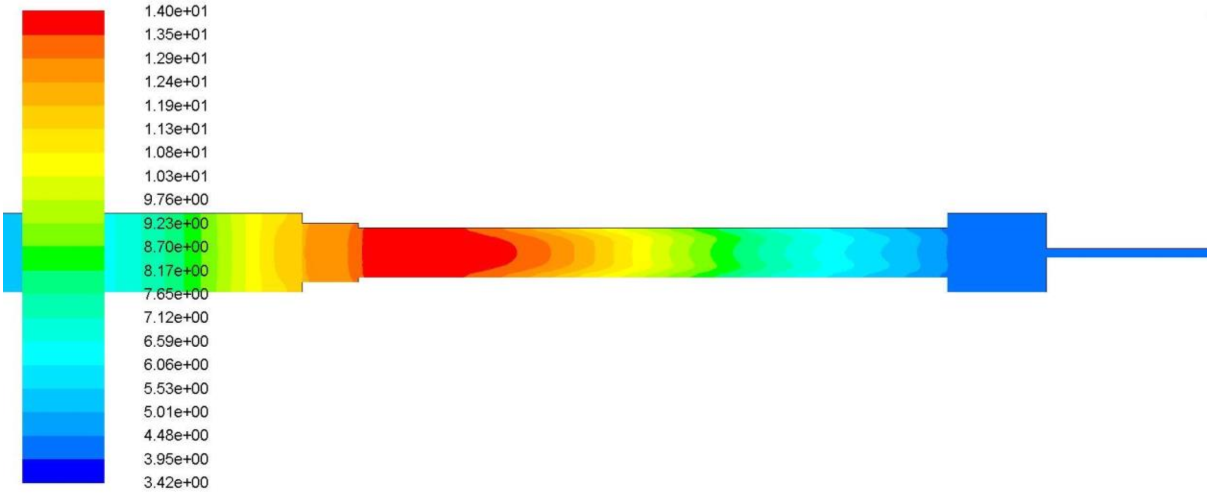

Fig. 5.13 Contours of Density for case 2

In comparison with case1, which represents the same physical system and boundary conditions but with zero cooling load, the cold end stabilizes at an essentially higher temperature. This is obviously expected because when a heat load is applied to the system, the operating cold tip temperature should increase. Figure5.10 and 5.11 show the temperature and density circulations along the entire simulated system, respectively. The contours of temperature and density are shown in Fig.5.12 and Fig.5.13 respectively. These contours are qualitatively similar to the contours depicted in Figures 5.6 and 5.7.

The results of fluent showed that in the for adiabatic (case-1), the temperature reached at the cold end is 74.8K. When there is constant heat load of 1W was executed at CHX, its temperature achieved at the cold end was 96.9K.

CHAPTER 6

Conclusion

The ITPTR frameworks, working in periodic steady mode by an assortment of conditions of boundary, were mathematically solved utilizing Fluent of CFD and target was to exhibit the suitability of simulation of ITPTC in CFD and also to inspect the multi-dimensional stream and heat transfer properties. CFD reproductions demonstrated that a 1D investigation can be satisfactory just when every one of the segments of the inertance tube PTR have expansive length-to-diameter proportions. Critical impacts of multi-dimensonal and operational liquid distribution happen when one or more parts have moderately small ratios of length to diameter. The distribution pattern weakens the general execution of the framework.

Two separate simulations are investigated for ITPTR. One simulation expect an adiabatic cold heat-exchanger; another accept a heat load of 1W. Both simulation began by an expected uniform framework temperature, and proceeded till steady periodic conditions are accomplished. The CFD model of transient phenomenon effectively predicts pulse tube cryocooler performance through understanding the $Navier-Stokes\ Equations$ for momentum transfer and heat transfer of fluid, alongside the ideal gas condition. In the Fluent simulation the wall-thickness of the segments are neglected. However there is constantly some loss of conductance and it requires more research to account these impacts.

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